Neutrinos and Dark Matter
in the minimal $B − L$ SUSY Model
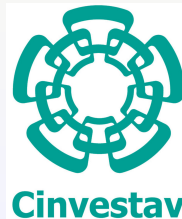
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in collaboration with
Dr. A. Pérez-Lorenzana

based on
arXiv:1105.0713
arXiv:1109.xxxx

LHCphenonet

Cinvestav

Outline

Neutrinos and Cosmology

Observational inconsistencies are motivating to look for physics beyond the SM,

- It can not explain neutrino masses,
- It does not explain the origin of the cosmological ingredients,
- Galactic Rotation Curves
- Gravitational Lensing
- "Bullet Cluster". . .
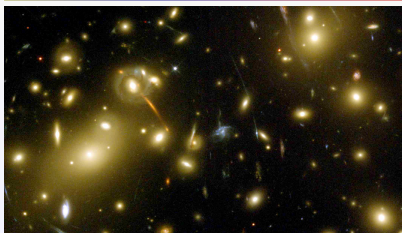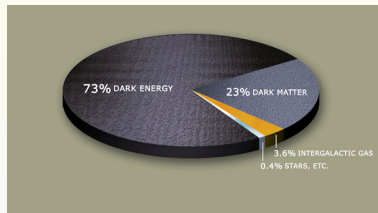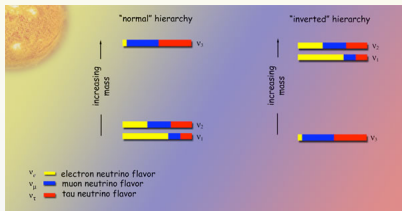
Neutrino mass in SM extensions

- In the SM, there is only one helicity state per generation for neutrinos.
- We also know that $B - L$ current is conserved to all orders in perturbation theory.
- Without the right handed component, it is not possible to build a mass term for neutrinos.
- The inclusion of right handed neutrinos preserve $B - L$ anomaly free.
- The Majorana term breaks $B - L \Rightarrow$ it must be broken somehow.

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In general, neutrino masses can be analyzed via,

$$\delta\mathcal{L} = h\sigma\bar{\nu}_R^c \nu_R + h'\bar{L}\tilde{H}\nu_R$$

and it has a direct connection with the DM problem and the barionic asymmetry of the universe.

- It suggest as a natural symmetry to $SU(2)_L \times U(1)_Y \times U(1)_{B−L}$.
- It is needed to include 3 families of right handed neutrinos to preserve anomaly cancelation.
- Supersymmetry can help to know the value at low energies of the parameters of the model, also the breaking scale of $U(1)_{B−L}$.

The supersymmetric $B - L$ model

The superpotential that contains neutrino masses is,

$$\Delta W = \bar{N}\mathbf{Y}_N^D L H_u + N\mathbf{Y}_N^M N \sigma_1 + \mu' \sigma_1 \sigma_2,$$

where under $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$ the extra superfields transform as
$$\bar{N} = (\mathbf{1},\mathbf{1},0,-1) \quad \sigma_1 = (\mathbf{1},\mathbf{1},0,2) \quad \sigma_2 = (\mathbf{1},\mathbf{1},0,-2).$$

Kinetic terms are also included,

$$\Delta K \quad = \quad \hat{N}^\dagger e^{2V} \hat{N} + \hat{\sigma}_1^\dagger e^{2V} \hat{\sigma}_1 + \hat{\sigma}_2^\dagger e^{2V} \hat{\sigma}_2,$$

And the gauge part,

$$W_{(B-L)}^\alpha W_{\alpha(B-L)}|_{\theta\theta} = -2i\tilde{Z}_{B-L}\sigma^\mu \partial_\mu \bar{\tilde{Z}}_{B-L} + D^2 - \frac{1}{2}A_{\mu\nu}A^{\mu\nu} - \frac{i}{4}\tilde{A}_{\mu\nu}A^{\mu\nu}$$

The soft breaking term, which involves the new scalars is,

$$\Delta \mathcal{L}_{SB} = \frac{1}{2}M_{B-L}\tilde{Z}_{B-L}\tilde{Z}_{B-L} + \tilde{\bar{N}}\mathbf{h}_N^D \tilde{L} H_u + \tilde{N}^c \mathbf{h}_N^M \tilde{N}\sigma_1 + B'\sigma_1\sigma_2$$
$$+ m_{\sigma_1}^2 \sigma_1^\dagger \sigma_1 + m_{\sigma_2}^2 \sigma_2^\dagger \sigma_2 + \tilde{N}^\dagger m_N^2 \tilde{N}$$

We do not need to impose $R-$parity, because $R-$parity violating terms are forbidden by gauging under $U(1)_{B-L}$.

Unification

RGE were obtained by considering that $U(1)$ gauge groups are orthogonal. In the most general case one needs to consider the mixing between these abelian groups.
F. del Aguila, G.D. Coughlan, M. Quiros, Nucl. Phys. B 307, 633 (1988).

Within this approach we have,

$$\alpha_i^{-1}(m) = c_i \left[\alpha_i^{-1}(m_Z) + (2\pi)^{-1} b_i \ln \left(\frac{m}{m_Z} \right) \right],$$

where c_i embedding factors can be computed from the normalization of the gauge groups at the GUT scale. In this sense, it is not needed to know the unifying gauge group.
And b_i it is also known from

$$b = 3C_1(G) - \sum_R C_2(R)$$

where $C_1(G)$ is the quadratic Casimir invariant, and $C_2(R)$ the Dynkin index. Therefore

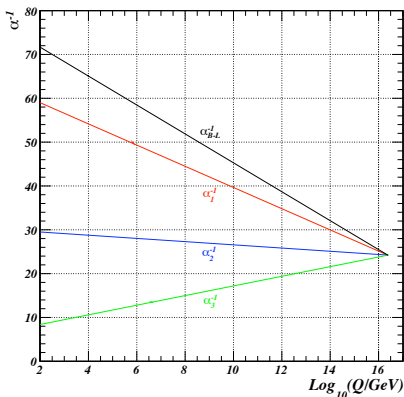$$(c_1, c_2, c_3, c_{B-L}) = (3/5, 1, 1, 3/8),$$
$$(b_1, b_2, b_3, b_{B-L}) = (-11, -1, 3, -24).$$

Unification

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Low energy value for the $B - L$ gauge coupling is

$$g_{B-L}(m_Z) \approx 0.2565$$

This value put a constraint on the associated $B - L$ gauge boson given by LEP
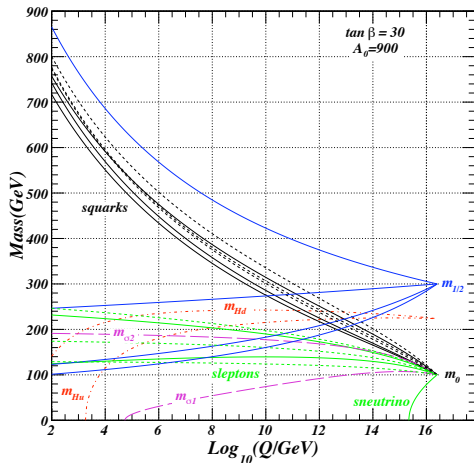
$$M_{B-L}/g_{B-L} > 6\,TeV$$

M. Carena et al.
Phys. Rev. D 70, 093009 (2004)

Therefore

$$M_{B-L} > 1.5 \text{ TeV}$$

Sparticle spectrum

$U(1)_{B-L}$ is broken by $\langle \sigma_1 \rangle$ and $\langle \tilde{N} \rangle$.

Moreover, right-handed sneutrino vev will contribute to the mass of the associated $B - L$ gauge boson,

$$M^2_{B-L} = g^2_{B-L}(4v^2_{\sigma_1} + 4v^2_{\sigma_2} + v^2_{\tilde{N}})$$

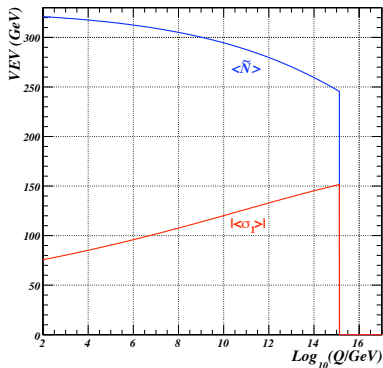The lightest neutralino corresponds to $\tilde{Z}_{B-L}$.

Breaking of $U(1)_{B-L}$ occurs too fast !!!

$B - L$ breaking

$\tilde{N}$ becomes negative so fast, so it is worth asking the vev scale at low energies; the potential includes a mixing with the σ_1, therefore,

$$V(\tilde{N}, \sigma_1) = \left(|y_M|^2 + \frac{1}{8} g_{B-L}^2 \right) |\tilde{N}|^4 + m_N^2 |\tilde{N}|^2 + \frac{1}{8} g_{B-L}^2 |\sigma_1|^4 + \left\{ \mu' + m_{\sigma_1}^2 \right\} |\sigma_1|^2$$
$$+ 4 |y_M|^2 |\tilde{N}|^2 |\sigma_1|^2 + a_M \sigma_1 |\tilde{N}|^2$$

and the numerical solution is

Even if both fields acquire a vev almost at the GUT scale, their vevs are at the GeV scale.

The phase appearing for $\langle \sigma_1 \rangle$ has been considered for Inflation and Baryogenesis models.

D. Delepine et al.
Phys. Rev. Lett. 98, 161302 (2007)

Neutrino mass

Due to RGE, we have found that the elements of the neutrino mass matrix will have $B - L$ components, other than the expected Majorana term. In order to find the corresponding mass matrix we need to implement a double *see saw* mechanism. This feature rise by the fact that the neutrinos and neutralinos are mixed in the same mass matrix.

P. Fileviez-Perez and S. Spinner, Phys. Lett. B 673, 251 (2009).

The mass mixing between neutrinos and neutralinos has the following form,

$$\mathbf{M}_{\nu\tilde{\chi}^0} = \begin{pmatrix} 0 & \frac{y_D v s_\beta}{\sqrt{2}} & \mathbf{\Lambda} \\ \frac{y_D v s_\beta}{\sqrt{2}} & \frac{y_M v' s_\theta}{\sqrt{2}} & \mathbf{\Omega} \\ \mathbf{\Lambda}^T & \mathbf{\Omega}^T & \mathbf{M}_{\tilde{\chi}^0} \end{pmatrix}$$

where we have taken the basis $(\nu_L, N, \tilde{\chi}^0)$. The neutralino mass matrix has been also modified and now read, in the basis $\left(\tilde{\psi}^0\right)^T = (\tilde{B}^0 \quad \tilde{W}^0 \quad \tilde{H}_d^0 \quad \tilde{H}_u^0 \quad \tilde{Z}_{B-L}^0 \quad \tilde{\sigma}_1 \quad \tilde{\sigma}_2)$, as,

$$\mathbf{M}_{\tilde{\chi}^0} = \begin{pmatrix} \mathbf{M}_{\tilde{\chi}_{\mathbf{MSSM}}^0} & \mathbf{0} \\ \mathbf{0} & \mathbf{M}_{\tilde{\chi}_{\mathbf{B-L}}^0} \end{pmatrix}$$

where all matrices are,

$$\mathbf{M}_{\tilde{\chi}^0_{\mathbf{MSSM}}} = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix},$$

and

$$\mathbf{M}_{\tilde{\chi}^0_{\mathbf{B-L}}} = \begin{pmatrix} M_{B-L} & 2\sqrt{2}g_{B-L}v's_\theta & -2\sqrt{2}g_{B-L}v'c_\theta \\ 2\sqrt{2}g_{B-L}v's_\theta & 0 & -\mu' \\ -2\sqrt{2}g_{B-L}v'c_\theta & -\mu' & 0 \end{pmatrix}$$

$$\mathbf{\Lambda} = \begin{pmatrix} 0 & 0 & 0 & \frac{v_R y_D}{\sqrt{2}} & 0 & 0 & 0 \end{pmatrix},$$

$$\mathbf{\Omega} = \begin{pmatrix} \mathbf{0}_{1\times 4} & -\sqrt{2}g_{B-L}v_R & \frac{y_M v_R}{\sqrt{2}} & 0 \end{pmatrix},$$

and we have taken

$$\langle \tilde{N} \rangle \equiv \frac{v_R}{\sqrt{2}}, \langle \sigma_1 \rangle \equiv v's_\theta, \text{ and } \langle \sigma_2 \rangle \equiv v'c_\theta$$

Therefore, the neutrino mass matrix is given by,

$$[M_\nu]_{11} = \frac{v_R^2 y_D^2}{4\mu \left(t_\beta - \frac{M_1 M_2 \mu c_\beta^{-2}}{m_Z^2 (M_1 + M_2 + (M_1 - M_2) c_{2\theta_W})} \right)},$$

$$[M_\nu]_{12} = \frac{v y_D s_\beta}{\sqrt{2}},$$

$$[M_\nu]_{22} = \frac{v' s_\theta y_M}{\sqrt{2}} - \frac{2 g_{B-L}^2 v_R^2 (\mu' - v' y_M c_\theta)^2}{\mu'^2 \left(M_{B-L} - 4 g_{B-L}^2 s_{2\theta} \frac{v'^2}{\mu'} \right)}.$$

A random scan over the parameter space let the mass of the right handed neutrino to be,

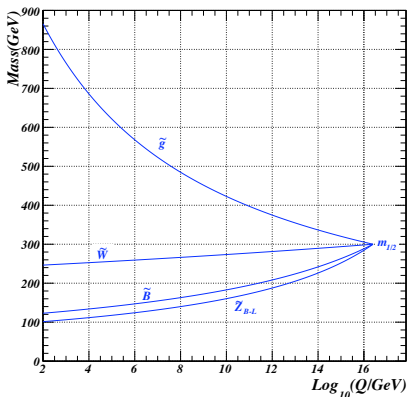$$\boxed{m_N > \mathcal{O}(1) \text{ GeV},}$$

by requiring the cosmological constraint $\sum_i m_{\nu_i} < 2$ eV to be satisfied.
J. Lesgourgues and S. Pastor, Phys. Rept. 429, 307 (2006).

$B - L$ Neutralino

- In this model, which particle is the LSP ?!?!
- The lightest gaugino belongs to the $U(1)_{B-L}$ sector.
- Nevertheless, we can still tune the μ' parameter and, therefore the lightest particle would be $\tilde{\sigma}_{1,2}$.
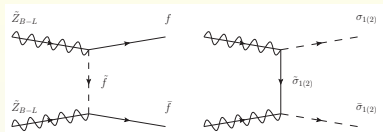

$$\mathbf{M}_{\tilde{\chi}^0_{\mathbf{B-L}}} = \begin{pmatrix} M_{B-L} & \Delta s_\theta & -\Delta c_\theta \\ \Delta s_\theta & 0 & -\mu' \\ -\Delta c_\theta & -\mu' & 0 \end{pmatrix}$$

where $\Delta = 2\sqrt{2} g_{B-L} v'$

DM Relic Density

If the DM component is dominated comple-
tely by $\tilde{Z}_{B-L}$, the processes that contribute
to the Relic Density are those in which an
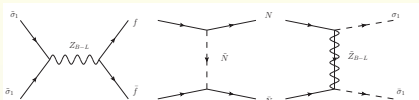sfermion or a $\tilde{\sigma}_i$ is exchanged in the t and u
channel.

S. Khalil and H. Okada, Phys. Rev. D 79, 083510 (2009).

Points which satisfied the neutrino mass
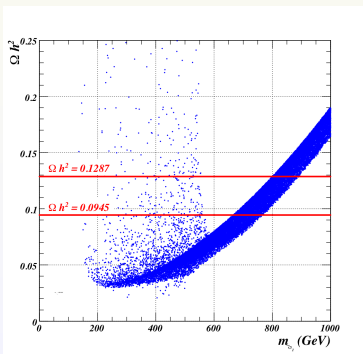constraint have been used to compute Ωh^2.

For a $\tilde{Z}_{B-L}$ mass in the range between 150
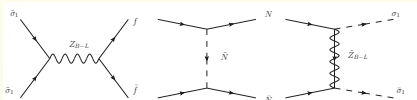and 900 GeV, we are in agreement with
WMAP.
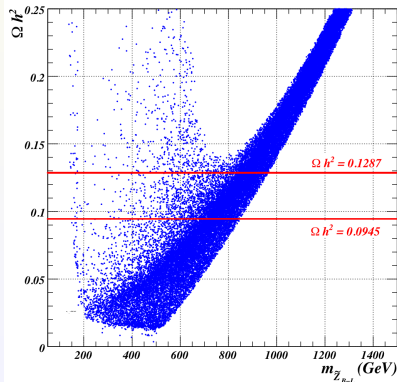
If the DM component is dominated by $\tilde{\sigma}_1$,

Taking the same considerations, we find the following solution,
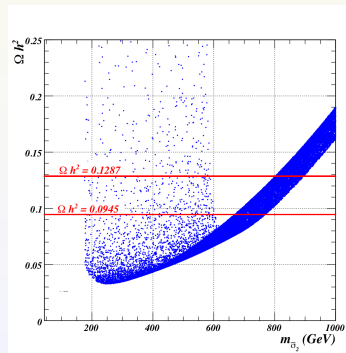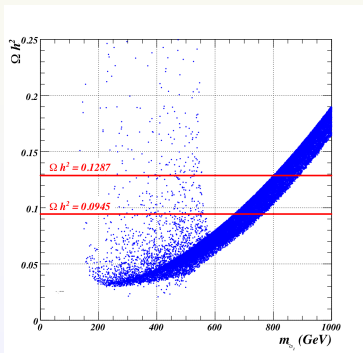
If the DM component is dominated by $\tilde{\sigma}_1$,   And, if the DM composition is $\tilde{\sigma}_2$ dominated,

And the numerical solution is

Taking the same considerations, we find the following solution,

Conclusions

- We have studied the supersymmetric extension of the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$, where we have added a right handed neutrino superfield, and two extra $B - L$ Higgses.

- We calculated the renormalization group equations for all the parameters of the model.

- By requesting a unification at the GUT scale, we have calculated the associated gauge coupling $g_{B-L}(m_Z) \approx 0.2565$, implying immediately $M_{B-L} > 1.5\,TeV$.

- The breaking of $U(1)_{B-L}$ is mediated by the sneutrino and the $B - L$ Higgs fields. Their vevs at low energies are under control due to the contributions of all the sparticles.

- By applying a double *see-saw* procedure, neutrinos can acquire a mass which can give solve some problems in the neutrino phenomenology.

- We have studied the contribution to Ωh^2 by considering that the $B - L$ sector contains the LSP.

Thanks...

Gaugino masses

$$\beta_{M_i} = 2c_i g_i^2 M_i, \text{where} \quad i = 1, 2, 3, B-L$$

Yukawa and μ terms

$$\Delta\beta_{y_t} = y_t \left\{ y_D^2 - g_{B-L}^2/6 \right\}, \qquad \Delta\beta_{y_b} = -y_b g_{B-L}^2/6,$$

$$\Delta\beta_{y_\tau} = y_\tau \left\{ y_D^2 - 3g_{B-L}^2/2 \right\}, \qquad \Delta\beta_\mu = \mu y_D^2,$$

$$\beta_{y_D} = y_D \left\{ 4y_D^2 + 3y_t^2 + y_M^2 - 3g_1^2/5 - 3g_2^2 - 3g_{B-L}^2/2 \right\},$$

$$\beta_{y_M} = y_M \left\{ 3y_M^2 + 4y_D^2 - 9g_{B-L}^2/2 \right\},$$

$$2\beta_{\mu'} = \mu' \left\{ y_M^2 - 3g_{B-L}^2 \right\},$$

Soft parameters

$$\Delta\beta_{a_t} = a_t \left\{ y_D^2 - g_{B-L}^2/6 \right\} + y_t \left\{ 2a_D y_D + g_{B-L}^2 M_{B-L}/3 \right\},$$

$$\Delta\beta_{a_b} = -a_b g_{B-L}^2/6 + y_b g_{B-L}^2 M_{B-L}/3,$$

$$\Delta\beta_{a_\tau} = a_\tau \left\{ y_D^2 - 3g_{B-L}^2/2 \right\} + y_\tau \left\{ 2a_D y_D + 3g_{B-L}^2 M_{B-L} \right\},$$

$$\beta_{a_D} = a_D \left\{ 12y_D^2 + 3y_t^2 + 2y_M^2 + y_\tau^2 - 3g_1^2/5 - 3g_2^2 - 3g_{B-L}^2/2 \right\}$$
$$+ y_D \left\{ 6a_t y_t + 2a_M y_M + a_\tau y_\tau + 6g_1^2 M_1/5 + 6g_2^2 M_2 \right.$$
$$\left. + 3g_{B-L}^2 M_{B-L} \right\},$$

$$\beta_{a_M} = a_M \left\{ 15y_M^2 + 8y_D^2 - 9g_{B-L}^2/2 \right\} + \left\{ 8a_D y_D + 9g_{B-L}^2 M_{B-L} \right\}.$$

Sparticle masses

$$\Delta\beta_{m^2_{Q_3}} = -g^2_{B-L}M^2_{B-L}/3 + g^2_{B-L}S'/4,$$

$$\Delta\beta_{m^2_{u_3}} = -g^2_{B-L}M^2_{B-L}/3 + g^2_{B-L}S'/4,$$

$$\Delta\beta_{m^2_{d_3}} = -g^2_{B-L}M^2_{B-L}/3 + g^2_{B-L}S'/4,$$

$$\Delta\beta_{m^2_{e_3}} = -3g^2_{B-L}M^2_{B-L} - 3g^2_{B-L}S'/4,$$

$$\Delta\beta_{m^2_{L_3}} = 2y^2_D\left\{m^2_{H_u} + m^2_{L_3} + m^2_{N_3}\right\} + 2a^2_D - 3g^2_{B-L}M^2_{B-L}$$
$$- 3g^2_{B-L}S'/4,$$

$$\beta_{m^2_{N_3}} = 4y^2_D\left\{m^2_{H_u} + m^2_{L_3} + m^2_{N_3}\right\} + 4y^2_M\left\{m^2_{\sigma_1} + m^2_{N_3}\right\}$$
$$+ 4(a^2_M + a^2_D) - 3g^2_{B-L}M^2_{B-L} - 3g^2_{B-L}S'/4,$$

Higgs masses

$$\Delta\beta_{m^2_{H_u}} = 2y^2_D\left\{m^2_{H_u} + m^2_{L_3} + m^2_{N_3}\right\} + 2a^2_D, \quad \Delta\beta_{m^2_{H_d}} = 0,$$

$$\beta_{m^2_{\sigma_1}} = 2y^2_M\left\{m^2_{\sigma_1} + m^2_{N_3}\right\} + 2a^2_M - 12g^2_{B-L}M^2_{B-L} - 3g^2_{B-L}S'/2,$$

$$\beta_{m^2_{\sigma_2}} = -12g^2_{B-L}M^2_{B-L} + 3g^2_{B-L}S'/2,$$

$$S' = 2m^2_{\sigma_2} - 2m^2_{\sigma_1} + Tr[2m^2_Q - 2m^2_L + m^2_u + m^2_d - m^2_e - m^2_N].$$

Relic Density

In order to calculate Ωh^2, it is needed to solve the Boltzmann equation,

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma v \rangle [n_\chi^2 - (n_\chi^{eq})^2]$$

and using the variable $Y = n_\chi / s$, we can find,

$$\Omega_\chi h^2 = \frac{\rho_\chi}{\rho_{crit}/h^2} \approx 2{,}82 \times 10^8 Y_\infty (m_\chi / GeV)$$

and we can calculate numerically Y_∞ by using

$$Y_\infty^{-1} = 0.264 g_*^{1/2} m_{Pl} m_\chi \left[\frac{a}{x_f} + \frac{3b}{x_f^2} \right]$$

$$x_f = Ln \left[c(c+2) \frac{0.0764 m_{Pl}(a + 6b/x_f)m_\chi}{\sqrt{g_* x_f}} \right]$$

where a and b are the constants that appears in the expansion

$$\sigma v = a + bv^2 + \dots$$

in the limit where v is small.

Higgs masses

MSSM Scalar masses have been also modified. The main differences will appear because of the mixing between the $B - L$ and the MSSM scalars.

In order to compute the scalar masses, we need to consider all the scalar fields, therefore, in the basis

$\Phi = \begin{pmatrix} \tilde{\nu}_L & \tilde{\nu}_L^\dagger & \tilde{N} & \tilde{N}^\dagger & \sigma_1 & \sigma_1^* & \sigma_2 & \sigma_2^* & H_u^0 & H_u^{0*} & H_d^0 & H_d^{0*} \end{pmatrix}^T$, we can write the lagrangian,

$$\mathcal{L} = \frac{1}{2} \Phi^T M_\Phi^2 \Phi,$$

such that M_Φ^2 is,

$$M_\Phi^2 = \begin{pmatrix} M_{B-L}^2 & M_{mix}^2 \\ (M_{mix}^2)^T & M_{MSSM-Higgs}^2 \end{pmatrix}$$

but M_{mix}^2 elements are proportional to the Yukawa parameters, therefore, we can neglect them, as first approximation, and the MSSM Higges and the $B - L$ ones are orthogonal.